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Impact of various biodiesel fuels obtained from edible and non-edible oils on engine exhaust gas and noise emissions

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ABSTRACT

Increasing demand for fossil fuels due to the luxurious lifestyle, significant growth of population, transportation and the basic industry sectors has caused serious environmental problems. Moreover, a rapid decline in the fossil fuels has led scientists and researchers to look for new alternatives. In this regard, alternative fuels such as biofuels are becoming important increasingly due to environmental and energy concerns. Biofuels are commonly referred to as first generations, which are produced primarily from food crops. However, the use of edible oil to produce biodiesel in many countries is not feasible in view of a big gap in the demand and supply of such oils for dietary consumption.

This paper critically reviews the facts and prospects of biofuel utilization especially, three edible biodiesels namely soybean, rapeseed, palm and two non-edible viz. jatropha and cottonseed to reduce engine exhaust gas, noise emission and petro dependency. Based on various biofuel feedstocks, this paper generally found that biodiesel fuels are considered as offering many benefits, including sustainability, reduction of greenhouse gas emissions and many harmful pollutants along with noise emission, regional development, social structure and agriculture, and security of supply.

Contents

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1. Introduction

The consumption of energy has ever increasing trend due to two reasons, mainly: (1) a change in the lifestyle and (2) the significant growth of population. Two of the main contributors are the transportation and the basic industry sectors. This increase of energy demand has been supplied using fossil resources (crude oil, natural gas and coal, principally), which have caused serious environmental impacts as global warming, acidification, deforestation, ozone depletion, eutrophication and photochemical smog, among others [1]. The last two years experienced the Deepwater Horizon oil spill off the Gulf of Mexico, the Fukushima-Daiichi nuclear accident in Japan, and the Arab Spring, which led to oil supply disruptions from Middle East [2]. These trends and events, when taken together, emphasize the need to rethink our global energy system.

Owen et al. [3] reported that current proved reserves of liquid fuels have the capacity to serve just over half of Business As Usual (BAU) demand until 2023. Therefore alternative fuels or biofuels are becoming important increasingly due to environmental and energy concerns [4]. U.S. Energy Information Administration (EIA) shows a projection on world's consumption of marketed energy from all fuel sources through 2035, which supports the increasing trend of renewable's consumption [5]. This also reports renewable energy as the world's fastest growing form of energy with the renewable share of total energy use increases from 10% in 2008 to 14% in 2035 in its reference case. International Energy Agency (IEA) says, biofuels could provide 27% of total transport fuel and contribute, in particular, to the replacement of diesel, kerosene and jet fuel by 2050 [6]. The projected use of biofuels could avoid around 2.1 gigatonnes (Gt) of CO_2 emissions per annum when produced sustainably. Biofuels are commonly referred to as first generation, which are produced primarily from food crops such as grains, sugar cane and vegetable oils, or second generation, which covers a variety of technologies (e.g., inedible oils, lignocellulosic biomass or woody crops, agricultural residues or waste) currently in the pipeline [7,8]. The increasing criticism of the sustainability of many first-generation biofuels has raised attention to the potential of so-called second-generation biofuels.

The Kyoto Protocol was a significant step for reduction of carbon dioxide and five other greenhouse gases as it set a legal-binding on quantitative emanation for industrialized nations. It indirectly introduced the concept of "carbon neutral fuel". There are many emission standards, which focus on regulating pollutants released by automobiles and other powered vehicles, which generally specify certain limiting value of the emissions of nitrogen oxides (NO_x), particulate matter (PM) or soot, carbon monoxide (CO), or volatile hydrocarbons. Traffic noise is the second environmental burden on health after air pollution according to the World Health Organization (WHO) [9].

Car manufacturers put lots of efforts to meet stringent regulations on exhaust emissions and noise radiation concurrently. This resulted in a new generation of diesel engines, more environment friendly and are in no way inferior to gasoline engines in terms of performance. In comparison with the gasoline engines, diesel engines have better output torque, reliability and durability. Besides, they burn 30% less fuel and emit 25% less CO_2 on average [10–12]. Even though the sound quality of diesel engines hugely improved, it remains inferior to gasoline engines and these sounds can be distinguished easily. Diesel engines produce knock which is very characteristic and unpleasant sound [10,13,14]. This may be the main drawback for diesel engines at a time when acoustical comfort has become an important criterion in selecting cars from the customer's viewpoint [13,15,16]. In this situation, biofuels need to satisfy certain criteria to be considered a sustainable and less objectionable option.

The objective of this report is to provide a literature review on state of the art of combined analysis of criteria emissions viz. NO_x, PM, CO, HC as well as noise emissions of diesel engines using biodiesel. Similar review works are done with performance and exhaust emission by many researchers [17–19]. However nobody has considered combined analysis so far. It also aims to guide the continuing study of suitability of biodiesel, and its blends as partial fossil-fuel substitutes. The report is molded with review on three first-generation biodiesel namely soybean, rapeseed, palm and two second-generation biodiesel viz. jatropha and cottonseed. The three first-generation biodiesels selection was influenced by their extensive use USA, European region and tropical region, e.g., India, Malaysia, etc. Two second generation biodiesels are selected because of rapidly growing research interest on them. The report mainly focusses on impacts of five specified biodiesels on criteria exhaust emissions and noise as well as their emission reduction techniques. Highly rated journals in scientific indexes are analyzed here. Since the combined study of Noise, Vibration and Harness (NVH) and exhaust of diesel engines are relatively less in indexed journals so non-indexed publications, such as SAE technical papers or some reports from reputed organizations have also been cited.

2. Diesel emissions

Diesel engine's emissions have changed significantly over the last 40 years because of improvements in engine technology, emission controls, and fuel preparation [20]. Diesel engine exhaust contains a wide range of gaseous and particulate phased organic and inorganic compounds with higher amounts of aromatics and sulfur. The particles have hundreds of chemicals adsorbed onto their surfaces; comprising many recognized or suspected mutagens and carcinogens. The gaseous phase also contains many toxic chemicals and irritants. These have serious adverse effect on human health and environmental impact [21–23]. The composition of diesel exhaust varies considerably depending on engine type and operating conditions, fuel, lubricating oil, and whether an emission control system is present. Generally, exhaust contains a higher amount of particulate matter (PM), oxides of nitrogen (NO_x), carbon monoxide (CO), unburned hydrocarbon (HC) and smoke. Moreover higher noise radiated form engine creates nuisance, which is also a matter of concern nowadays. Worldwide testing procedures and exhaust emission standards are shown in Fig. 1.

2.1. Particulate matter (PM)

Diesel engines are an influential source of particulate emissions. Particulate matter (PM) air pollution is an air-suspended mixture of solid and liquid particles that vary in number, size, shape, surface area, chemical composition, solubility, and origin [25,26]. PM is highly complex mixture of very fine particles and liquid droplets, which includes soot, HC Soluble Organic Fraction (SOF), water SOF and ash, present in the atmosphere. The size

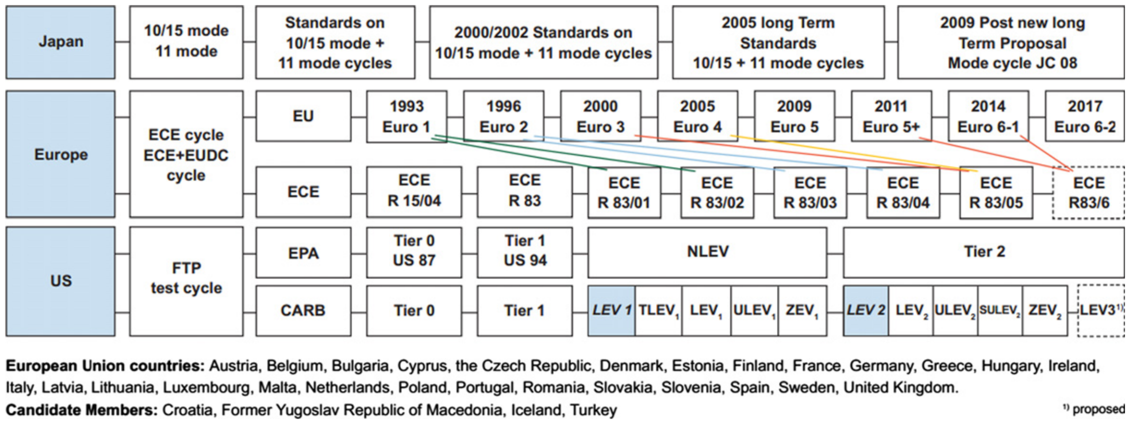


Fig. 1. Worldwide exhaust emission testing procedures and standards [24].

distribution of PM is trimodal, including coarse particles, fine particles, and ultrafine particles [27,28]. These particles exist in different shapes and densities in the air, and hence, the aerodynamic diameter has been recognized as a simple means of defining the size of particles [29]. Public health concern has roused about emissions because the particles in emissions are very small (more than 90% are less than 1 mm by mass) which makes them readily breathable. Soot part primarily consists of fractal-like carbonaceous accumulates in the size span of 30–500 nm [30]. High concentration of PM in ambient air causes degradation of lung function, cardiovascular diseases, irregular heartbeat, adverse birth, neurodegenerative disorders nonfatal heart attacks [25,31–34]. Smoke opacity is an indirect indicator of soot content in the exhaust gases. Therefore this parameter can be correlated with the fuel's tendency to form particulate matter (PM) during engine operation [35].

2.2. Nitrogen oxides (NO_x)

Nitrogen oxide is the generalized term for NO and NO_2 given with the formulae of NO_x. NO_x is the most harmful gaseous emissions from engines; the reduction of it is always the target for engine researchers and engine manufacturers. The formation of NO_x highly depends on in-cylinder temperatures, oxygen concentration, and residence time for the reaction to take place and air surplus coefficient. NO_x is generated during combustion by three mechanisms: thermal, prompt, and fuel. High combustion temperature (1800 K) breaks the strong triple bond of nitrogen molecules, disassociate into their atomic states and participate in a series of reactions with oxygen and generates thermal NO_x, commonly known as Zeldovich Mechanism [36,37].

According to prompt mechanism, formation of free radicals in the flame front of hydrocarbon flames leads to rapid production of NO_x. The fuel NO_x is formed by the reaction of nitrogen bound in the fuel with oxygen during combustion. The production process is complex because this includes of the order of 50 intermediate species and several hundred reversible reactions and true value of rate constants are still unknown. Volatile fuel nitrogen is evolved mainly as HCN (and NH_3) during the processes thermal and prompt NO_x are the dominant mechanisms in bio-diesel fuelled engines since; biodiesel does not contain fuel-bound nitrogen [38].

2.3. Hydrocarbon (HC)

CI engines have only about one-fifth the HC emissions of an SI engine as they operate with an overall fuel-lean equivalence ratio. The components in diesel fuel have higher molecular weights on average than those in a gasoline blend, and these results in higher boiling and condensing temperatures. There are two major causes of HC emissions in diesel engines under normal operating conditions: (1) fuel mixed to leaner than the lean combustion limit during the delay period; (2) undermixing of fuel which leaves the fuel injector nozzle at low velocity, late in the combustion process. At light load and idle, overmixing is especially important, particularly in engines of relatively small cylinder size at high speed. In IDI engines, the contribution from fuel in the nozzle sac volume is less important than with DI engines. However, other sources of low velocity and late fuel injection such as secondary injection can be significant [39].

2.4. Carbon monoxide (CO)

During combustion, CO is formed whenever charge is burned with an insufficient air supply. Even the amount of air which is theoretically sufficient to complete combustion, in practical cases it may not be complete. This will lead to incomplete combustion products containing some free oxygen and some carbon monoxide. The CO emissions in the exhaust represent lost chemical energy that is not fully utilized in the engine [40]. When the reaction temperature falls below 1500 K, the burning deteriorates and the amount of CO increases. The OH radical is the one which transforms CO to CO_2 [41]. When inhaled, it replaces the oxygen in the blood stream so that the body's metabolism cannot function properly. Small amounts of CO concentration slow down physical and mental activities and produce headaches, while large amounts can kill.

2.5. Noise emission

Sound is a natural phenomenon. It becomes noise when it has some undesirable effect on people or animals. Noise is a significant environmental problem across the world. Unlike chemical pollution, noise energy does not accumulate either in the body, or in the environment, but it can have both short-term and long-term adverse effects on people. Noise pollution can annoy, disturb sleep, affect the cognitive function in schoolchildren, cause physiological stress reactions and can cause cardiovascular problems in chronically noise-exposed subjects. Fifty thousand deaths, a quarter of a million cases of cardio vascular disease [9] and 5% of strokes [42] are estimated to be caused by traffic noise. Over a prolonged period of exposure, these effects may in turn increase the risk of cardiovascular disease and psychiatric disorders. World Health Organization (WHO) recognized effects of environmental noise, including annoyance, as a serious health problem more than a decade ago [43]. The health effects of noise pollution can be seen as a pyramid in Fig. 2, with the mildest but

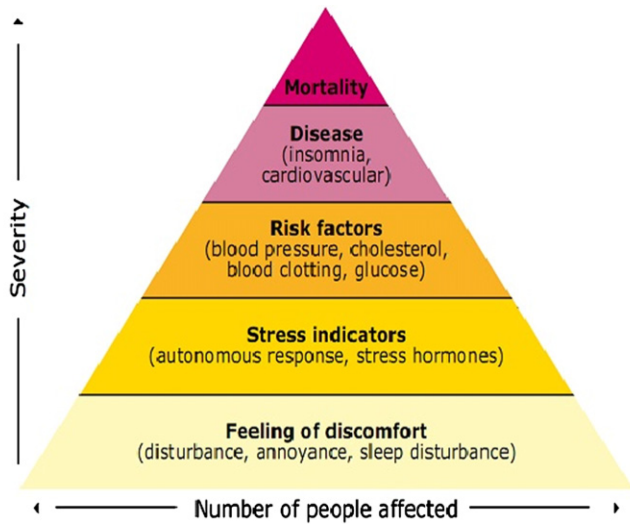


Fig. 2. WHO Pyramid of Health Effects of Noise [9].

not common effects at the bottom of the pyramid, and the least common but more severe at the top of the pyramid.

There are various studies to clarify the mechanism of noise and vibration in diesel engines and classified various sources and their contribution to the total engine noise. In general, internal-combustion engine radiated noise can be divided into mechanical noise, combustion noise and noise resulting from the accessories. Furthermore, combustion-related noise is divided into direct and indirect combustion noise as well as flow noise [44–46]. The combustion noise is purely a load dependent phenomenon. The conventional combustion process in diesel engines is considered as the most important source of noise [47–49]. Efforts are mainly concentrated on the overall level reduction of the combustion noise and improvement of sound quality, mainly oriented to customer satisfaction [50].

At the beginning of combustion, an abrupt pressure rise is produced, which stimulates an oscillation of the gas inside the combustion chamber [51]. This pressure rise inside the cylinder act directly on the walls of combustion chambers, causes vibration of the engine block. This in turn radiates the aerial noise. Moreover, a resonant oscillation of the gas inside the combustion chamber is also produced by the pressure gradient induced by combustion. This oscillation is controlled mostly by the bowl geometry and the gas temperature. Therefore, the resonance in the combustion chamber is a non-stationary process as the piston position changes continuously so as the bowl geometry and the gas temperature changes during the combustion process. The pressure force evolution is mainly dominated by the fuel-burning velocity, and this velocity is controlled by the injection rate [52–54]. Indirect combustion noises are produced by mechanical forces that are induced by the pressure forces through the mechanical systems in the cylinder and are due to piston slap, clearances, deformation, friction, etc. [53]. Therefore, both noises are characterized by the in-cylinder pressure evolution. The residual noise, produced by various sources, is referred to as mechanical noise [55–57]. The flow noise is radiated by intake and exhaust system of the engine [58–60]. Overall engine noise includes also pure mechanical noise as well as accessory drive noise. The poor maintenance, faulty adjustment of engine operational parameters and wear can cause changes in engine noise.

3. Biodiesel

The use of alternatives as a fuel has started from the beginning of the last century when Rudolph Diesel fueled a diesel engine with the oil of an African groundnut (peanut). Thus, the idea of using vegetable oil as a substitute for diesel fuel in engines was demonstrated by the inventor himself [61]. Now vegetable oils have become one of the promising renewable feedstocks for biodiesel production. Some tested sources are soybean, Palm, Sunflower, Rapeseed, Coconut, Jatropha, Cottonseed, Rubber seed, Pongamia, Neem, Jojoba, Mahua, Linseed, Candlenut seed, Castor etc. Global production of biofuels has been growing steadily over the last decade from 16 billion litres in 2000 to more than 100 billion litres in 2011. Today, biofuels provide around 3% of total road transport fuel globally (on an energy basis), and considerably higher shares are achieved in certain countries as reported by International Energy Agency (IEA) [6].

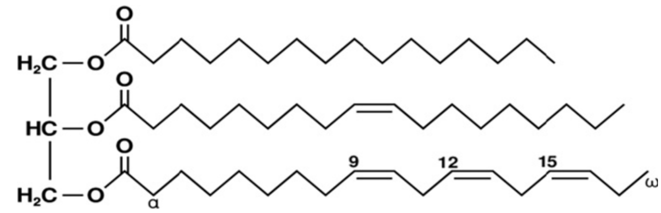


Fig. 3. Structure of a typical triglyceride molecule.

Diesel fuel contains solely carbon and hydrogen atoms arranged in straight chain or branched chain structures as well as aromatic configurations. The normal or straight chain structure is preferred for better ignition quality. Diesel fuel can contain both saturated and straight chain unsaturated hydrocarbons, but the latter are not present in large amounts, making oxidation a problem [62,63]. Vegetable oils and animal fats are principally composed of triacylglycerols (TAG) consisting of long-chain fatty acids chemically bound to a glycerol (1,2,3-propanetriol) backbone [64–67] as shown in Fig. 3. Vegetable oil consists of about 97% triglycerides; the remaining 3% for diglycerides, monoglycerides and free fatty acids. Fatty acid contents of selected vegetable oils are presented in Table 1. Feedstock availability varies according to geography, climate and economics. Thus, rapeseed is principally used in Europe; palm oil predominates in tropical countries, and soybean oil, and animal fats are primarily used in the US [68,69]. The size of vegetable oil molecule and the presence of oxygen in the molecule suggest that some fuel properties of vegetable oil are different from diesel fuel. Table 2 represents some of the main physical and chemical properties of the discussed biodiesels.

Biodiesel is defined as mono-alkyl esters of long-chain fatty acids (FAs) prepared from plant oils, animal fats or other lipids, designated B100 [96]. Congress adds an additional requirement that, the fuel should have life-cycle greenhouse gas (GHG) emissions at least 50% less than the baseline life-cycle GHG emission [72]. Advantages of biodiesel over petroleum diesel fuel include derivation from renewable feedstocks, superior lubricity and biodegradability, lower toxicity, essentially no sulfur and aromatics content, higher flash point, positive energy balance and reduced emissions of carbon monoxide (CO), total hydrocarbon (THC) and particulate matter (PM) [97–101]. Disadvantages include higher production cost, limited feedstock availability, inferior oxidative and storage stability, lower volumetric energy content; inferior cold flow properties, higher specific fuel consumption, and higher some oxygenated hydrocarbons and nitrogen oxides exhaust emissions [65,102–104]. The fuel properties of biodiesel must meet EN-14214 specifications in Europe and American Society of Testing and Materials (ASTM) D-6751 specifications in the USA, shown in Table 3.

4. Biodiesel impacts on emissions

Biodiesel is a clean-burning alternative fuel produced from renewable resources. The use of biodiesel creates less environmental

Table 1
Typical fatty acid composition of different vegetable oil (wt%) [70–72].

Fatty acid (*xx:y*)	Systemic name	Soybean oil	Palm oil	Rapeseed oil	Jatropha oil	Cottonseed oil
Lauric acid (C12:0)	Dodecanoic acid	0.1	0.1	–	–	0.1
Myristic acid (C14:0)	Tetradecanoic acid	0.1	1.0	–	–	0.7
Palmitic acid (C16:0)	Hexadecanoic acid	10.2	42.8	3.5	14.2	20.1
Palmitoleic acid (C16:1)	9-Hexadecenoic acid	–	–	–	1.4	–
Stearic acid (C18:0)	Octadecanoic acid	3.7	4.5	0.9	6.9	2.6
Oleic acid (C18:1)	9-Octadecenoic acid	22.8	40.5	64.1	43.1	19.2
Linoleic acid (C18:2)	9,12-Octadecadienoic acid	53.7	10.1	22.3	34.4	55.2
α-Linolenic acid (C18:3)	6,9,12-Octadecatrienoic acid (cis)	8.6	0.2	8.2	–	0.6
Arachidic acid (C20:0)	Eicosanoic acid	0.3	–	–	0.2	–
Behenic acid (C22:0)	Docosanoic acid	0.1	–	–	0.1	–
Saturates (%)		15.3	44.7	5.4	21.1	28.2
Unsaturates (%)		84.7	55.3	94.6	78.9	71.8

xx indicates number of carbon, and *y* number of double bonds in the fatty acid chain.

Table 2
Comparative physical and thermal properties of fossil diesel, edible and non-edible plant oils and biodiesels.

Common name	Properties								Reference
	Calorific value MJ/kg	Density at 288K kg/m^3	Flash point K	Pour point K	Kinematic viscosity at 300K mm^2/s	Carbon residue %, w/w	Cetane number	Iodine value mg I/g	
Soybean oil	39.62	914–920	527-603	260.8–273	65.40	0.27	36–38	117–143	[70,73–75]
Palm oil	36.51	915–918	540	241.3	39.60[a]		38–42	35–61	[76–78]
Rapeseed oil	36–37	900–930	493–519	241–262	39.20	0.3	37.60	94–120	[70,73,78–81]
Jatropha oil	38.85–39.77	918–920	513	276–278	49.9	0.2/0.44	45.00	94	[63,77,78,80,82]
Cotton-seed oil	39.64	915–924	507	258–279	34–50.10	0.24	35–50	90–140	[70,73–75,83,84]
Soybean biodiesel	39–40.5	885	414–440	266–272	3.9–4.65[a]	0.2	46–56	120–130	[72,74,85–90]
Palm oil biodiesel	37.4–38.2	864–871.6	408	287–289	4.05–5.1[a]	–	58–65.5	44–58	[72,85,87,88,90]
Rapeseed biodiesel	37	900–930	420–443	261	3.5–5.0[a]	–	50–56.6	110–122	[72,85,87,90–92]
Jatropha biodiesel	37.2–43.0	862–886	453–553[a]	267–279	3.0–5.65[a]	–	53–59	93–109	[90,91,93–95]
Cottonseed biodiesel	40.1–40.8	872–885	343–473	258–279	3.6–5.94	0.3	55–60	90–119	[74,83,91,93]

[a] At 313 K.

Table 3
Standard specifications for biodiesel and test methods (B100) [71,91,105,106].

Property	Units	EN-14214	EN test method	ASTM-D6751	ASTM test method
Density at 288 K	g/cm^3	0.86–0.90	EN ISO 3675 or 12185	–	–
Viscosity at 313 K	mm^2/s	3.50–5.00	EN ISO 3104	1.9-6.0	D445
Flash point	°C	120 min	EN ISO 3679	130 min	D93
Cetane number	–	51 min	EN ISO 5165	47 min	D613
Sulphur content	mg/kg	10.0 max	EN ISO 20846; EN ISO 20884	15.0 max	D5453
Phosphorus content	mg/kg	10.0 max	EN 14107	10.0 max	D 4951
Water content	mg/kg	500 max	EN ISO 12937	500 max	D2709
Acid number	mg KOH/g	0.50 max	EN 14104	0.80 max	D664
Free glycerin	%mass	0.02 max	EN 14105, EN 14106	0.02 max	D6584
Total glycerine	%mass	0.25 max	EN 14105	0.24 max	D6584
Sulfated ash content	%mass	0.02 max	ISO 3987	0.02 max	D874
Methanol content	%mass	0.20 max	EN 141110	–	
Monoglycerides	%mass	0.80 max	EN 14105	–	
Diglycerides	%mass	0.20 max	EN 14105	–	
Triglycerides	%mass	0.20 max	EN 14105	–	
Ester content	%mass	96.5 min	EN 14103	–	
Linolenic acid methyl ester	%mass	12.0 max	EN 14103	–	
Carbon residue[a]	%mass	–	–	0.05 max	D4530
Iodine value	–	120 max	EN14111	–	
Oxidation stability, at 383K	Hour	6 min	EN 14112	–	
Copper corrosion (3 h, at 323 K)	Degree of corrosion	No. 1	EN ISO 2160	No. 3	D130
Distillation 90% recovered	°C	–		360 max	D 1160

[a] Carbon residue shall be run on the 100% sample.

impacts than petroleum oils. Among the four criteria emissions, biodiesel (and biodiesel blends) has a strong beneficial effect on hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) emissions but variable effect on Nitrogen oxides (NO_x) emissions. Generally slightly increase in NO_x is observed with use of biodiesel. This increase is referred to as the “biodiesel NO_x effect”

[107,108]. According to a life cycle study performed by the United States Department of Agriculture (USDA) and the Department of Energy, the production of biodiesel compared to the production of petroleum fuels generates 78% less carbon dioxide, 79% less wastewater, and 96% less hazardous waste [109]. Biodiesel has the highest energy balance (3.5) of any other fuel, meaning for every unit of fossil energy needed to produce biodiesel, 3.5 units of energy are gained [110]. Noise emission also showed a decreasing trend and good noise quality with biodiesel fuel [46,111,112].

The structural features influence the physicochemical properties of biodiesel molecules. Biodiesel fuels are mainly composed of medium-chain to long-chain (C16–C18) fatty acid methyl esters, for which the main structural difference is consequently, the number of double bonds, i.e., the degree of unsaturation. Higher numbers of double bonds represent a greater degree of unsaturation. Generally, cetane number, heat of combustion, melting point, and viscosity of neat fatty compounds increase with increasing chain length and decrease with increasing unsaturation [113,114] of the FAME molecule. The heating value, melting point, cetane number, viscosity and oxidation stability decreases whereas density, bulk modulus, fuel lubricity and iodine value increases as the degree of unsaturation increases. A strong correlation between the degree of unsaturation and the properties of alkyl esters has been reported [115,116]. It has also been observed that, biodiesel molecular structure has a substantial impact on combustion and hence emissions.

4.1. Particulate matter (PM)

The biodiesel blends have significant positive influence on smoke and particulate matter emissions. Particulate matter emissions typically decrease significantly for biodiesel [117–120]. Causes presented in the literatures include oxygenation effects [121] and chemical kinetics effects [117,122,123]. Most reports showed a larger decrease in PM emissions at high load operation conditions. This trend was attributed to the fact that particles are mainly formed during diffusion combustion, and at high load most of the combustion process is diffusive. The higher oxygen content of ester fuel provided more oxygen for combustion and soot oxidation even in regions of the combustion chamber with fuel-rich diffusion flames [87,124–127]. Thus, the oxygen content of biodiesel is more effective in reducing PM emissions. The reduction of smoke opacity is mainly attributed to the reduction of aromatics and to the presence of oxygen in the ester molecules. Corporan et al. [128] reported smoke reduction happened due to the dilution of aromatics, which were considered as the soot precursors. Oxygenated additives had a dilution effect on the base fuel by replacing the highly sooting components of the base fuel with cleaner hydrocarbons or vice versa, including the reduction of the aromatics in the blended fuels [129,130]. Opposite trend is presented by few researchers as well [131].

4.2. Nitrogen oxides (NO_x)

NO_x emissions are widely known to increase for biodiesel over conventional diesel under most operating conditions [132–135]. Biodiesel NO_x increase is not quantitatively determined by a change in a single fuel property, but rather is the result of a number of coupled mechanisms whose effects may tend to reinforce or cancel one another under different conditions, depending on specific combustion and fuel characteristics [136]. There are numerous theories that attempt to explain the biodiesel NO_x effect including cetane number effects [137], soot radiation effects [138,139], bulk modulus effects [140], ECM-decision-making effects [141], prompt NO_x formation [142], changes in fuel composition that affect fuel spray or ignition patterns within the combustion chamber and adiabatic flame temperature effects [138,143,144].

4.3. Hydrocarbon (HC)

Biodiesel produces significantly lower HC emission than that of diesel fuel, is inferred by most of the researchers [137,145–148]. The reasons presented in the literatures point out two major causes, oxygen content effect and cetane number effect. The higher oxygen content of biodiesel molecule leads to a more complete and cleaner combustion [146,147] thus decreases HC emissions. The higher cetane number of biodiesel [149,150] reduces the combustion delay and decreases HC emissions. Lower HC emission can be attributed to lower volatility of biodiesel than that of diesel fuel [151]. Opposite trend has also been shown by some researchers [152,153].

4.4. Carbon monoxide (CO)

Decreasing CO emission with biodiesel is found by most of researchers [147,151,154–156]. The reasons resembles with the causes explained for HC emission. The oxygen content in the fuel, which enhances a complete combustion of the fuel, thus reduces CO emissions [155–157]. The increased biodiesel cetane number [150,158] lowers the probability of fuel-rich zones formation as well as advances injection and combustion, may also justify the CO reduction with biodiesel. Opposite result is also presented by few researches [152,153].

4.5. Noise emission

Chemical and physical properties of biodiesel influence the combustion efficiency thus the combustion noise. The radiated noise attenuation results from the reduction of the maximum pressure rise rate due to higher cetane number of biodiesel blends [46]. The higher the ignition delay the higher the liquid fuel injected before it starts to ignite. This makes the combustion pressure rise rate higher, as a higher amount of mass is exploded, which cause noise increase [159]. High viscosity of the blends may also explain the effect on the attenuation of noise radiation as a result of the influence on the start of injection and injection pressure [160,161]. In fact, spray properties e.g., droplet size, droplet momentum, degree of mixing and penetration, evaporation rate, radiant heat transfer rate etc.; alter due to differences in viscosity of the fuels. High viscosity provides worse pulverization, leads to increase in the fuel droplet size inside the combustion chamber and to a lower amount of fuel being burnt during the premixed regime, thus leading to a decrease of the maximum in-cylinder pressure. A change in any of these events might lead to different relative duration of the premixed versus diffusional burn stages [87]. The engine structure (block) acts as an attenuator of in-cylinder sound pressure, its design is critical for engine noise control [162,163]. Controlling the fuel burning velocity and hence the pressure gradient of the gas in the cylinder is the most efficient procedure for combustion noise reduction.

5. Feedstock effects on emissions

In this section, the effects of five specific feedstock viz. soybean, rapeseed, palm, jatropha and cottonseed biodiesels on exhaust gas and noise emission are discussed. Reduction techniques, as suggested by the studies are also highlighted.

5.1. Soybean biodiesel

The fatty acid composition of soybean oil represents higher percentage of unsaturation (about 84.7%) as presented in Table 1. This affects the physical and thermal properties of soybean biodiesel. Table 2 shows that due to higher unsaturation percentage soy-methyl ester has highest iodine value (range: 120–130 mg I/g) and lowest cetane number (range: 46–56) of the five considered biodiesels. It has also higher density (885 kg/m^3) compared to diesel fuel. Canakci [69] carried on the combustion analysis at steady state conditions in a four-cylinder turbocharged DI diesel engine at full load and 1400-rpm engine speed. He reported that start of fuel injection occurred earlier and ignition delay period was shorter than for the B100 fuel which matches the discussion in previous section. Table 4 emission data shows a considerable spread as there are variations in feedstock source, test equipment and operating condition, data acquisition instrument accuracy and ambient conditions. The following conclusions are attained:

- PM, soot and smoke level is reduced by soy methyl ester either without EGR or with EGR
- With the increase of biodiesel content in blends PM is reduced
- With the increase in fuel injection pressure, PM as well as smoke level decreases
- Advance in SOI results in lesser PM emission with it
- Optimal value of AFR, EGR fraction, rail pressure in common-rail fuel injection and SOI may lead to 50% reduction of PM
- NO_x increases with increased rail pressure, advance in SOI and biodiesel content
- CO emission decreases with increase in load and decrease in biodiesel content
- HC emission is generally reduced but there is no obvious trend

Emission reduction techniques as suggested from previous discussion:

- Optimal value of AFR, EGR fraction, rail pressure in common-rail fuel injection and SOI may lead to simultaneous reduction in PM, smoke, NO_x, CO, HC and overall noise level
- Higher fuel injection pressure will reduce PM, smoke level and CO emission
- High Efficiency Clean Combustion (HECC) will lead in higher HC reduction

5.2. Rapeseed biodiesel

Rapeseed oil has the highest percentage of unsaturation (about 94.6%) as in Table 1. This again affects the physical and thermal properties of rapeseed biodiesel. Table 3 shows that due to highest unsaturation percentage rapeseed methyl ester has highest density (range: 900–930 kg/m^3). Rapeseed oil has highest oleic acid percentage (64.1%) whereas soybean oil has highest linoleic acid percentage (53.2%). Iodine value (range: 110–122 mg I/g) and cetane number (50–56.6) is also similar to soybean biodiesel depending on the feedstock acquisition place. Kegl [156] carried out combustion analysis in a bus diesel engine with a mechanically controlled fuel injection M system using rapeseed biodiesel. He reported advanced injection timing and higher injection pressure for this engine which resembles with discussion in previous section. Table 5 emission data shows a considerable spread as there are variations in feedstock source, test equipment and operating condition, data acquisition instrument accuracy and ambient conditions. The following decisions can be made:

- Rapeseed Methyl Ester (RME) produces a high reduction of PM and smoke level
- Smoke emission is reduced with the increase of biodiesel content in blend
- PM increases as load increases
- Increase in fuel injection pressure reduces smoke level but increases NO_x
- NO_x emission generally increases (range: 4–21%) with rapeseed biodiesel
- NO_x emission increases with biodiesel content in blends
- RME produces large reduction in HC emission either without EGR or with EGR
- CO emission decreases with blend ratio as well as engine speed
- Higher injection pressure leads to higher CO emission but lower HC emission

Reduction techniques of emissions as suggested from review chart:

- Optimized injection timing and injection pressure setting may lead to simultaneous reduction in PM, smoke level, NO_x, CO, HC and overall noise level
- EGR has positive impact on NO_x emission reduction
- Rapeseed biodiesel produces an effective reduction in engine noise

5.3. Palm biodiesel

Palm methyl ester is mainly characterized by a high level of saturation percentage (about 44.7%) as in Table 1. This high level of saturation results in highest cetane number (range: 58–65.5), lowest iodine value (44–58 mg I/g) as well as density (range: 864–871.6 kg/m^3) (Table 3). Palm based biodiesel contain some amount of short chain fatty acids of low boiling point in addition to other fatty acids of high boiling point, during injection of biodiesel into a high temperature environment these fatty acids would break, vaporize and ignite, which in turn would provide sufficient heat for vaporization and ignition of fatty acids of higher boiling point present in the fuel, thereby it reduces ignition delay. Kousoulidou et al. [172] have done combustion analysis on a light-duty common-rail Euro 3 engine with B10 biodiesel. They found lower ignition delay compared to diesel in case of biodiesel blend. Sharon et al. [157] also found the same trend as they carried on experiment in a single cylinder DI, NA diesel engine with different blends. The reason behind is higher short chain fatty acids of low boiling point in addition to other fatty acids of high boiling point; during injection these fatty acids would break, vaporize and ignite faster, which in turn provide sufficient heat for vaporization and ignition of fatty acids of higher boiling point present in the fuel. Table 6 emission data shows a considerable spread as there are variations in feedstock source, test equipment and operating condition, data acquisition instrument accuracy and ambient conditions. The following decisions can be made:

- Palm biodiesel usually produces lower PM emission but greater smoke emission
- Smoke opacity increases with load and decreasing methyl ester content in blend
- NO_x increases with FAME content in blend
- Palm biodiesel have relatively lower impact on NO_x, although high impacts are also evidenced
- CO and HC emission reduction is dramatic (20% to more than 50%)

Table 4
Review of emissions analysis using soybean-biodiesel.

Test fuel/blend	Test equipment specification	Adjustments and/or modification and operating condition	Comparison with diesel fuel performance (% change) in exhaust gas and noise emissions					Ref.
			PM, soot and smoke	NO_x	CO	HC	Noise	
B0 & B100	Constant volume combustion chamber which simulate thermodynamic condition of diesel engine	Ambient gas temperature 800 to 1200 K Ambient gas density 15 kg/m^3 Ambient oxygen concentrations 21, 18, 15%	Total soot mass↑ with ambient gas temperature↑ and oxygen concentration↓ soot↓soot formation duration ↓	n/a	n/a	n/a	n/a	[164]
B100 & ULSD	Yanmar 1-cyl. DI[a], NA[b] AC[c] engine CR[d] 21.2 IT 15.5° (±0.5°) bTDC 6.2 kW at 3600 rpm Mechanical fuel pump-line injector	0, 25, 50, 75, and 100% of the connected generator rated output (the rated generator power is 80% of the rated power of the engine)	−56% (total particulate masses after 1 h test)	+56% (low load) −4% (medium load) −20% (high load)	−8% (low load) −34% (medium load) −27% (high load)	−64% (low load) −14% (medium load) −2.5% (high load)		[80]
B40 & ULSD	Ford 8-cyl. 6.4 L Powerstroke DI engine CR: 17.2 Maximum brake power 261 kW at 3000 rpm 2 VGT[e] Common-rail fuel injection	Constant Speed at 1500 rpm Variable Load 220 Nm, 470 Nm 640 Nm SOI −9; −7; −5; −3; −1; 1; 3 (aTDC) Variable injection pressure at all load EGR ratio (10±2)%	PM↑with SOI retardation or injection pressure ↓	NO_x ↑increase with SOI advance and injection pressure↑ At advanced SOI NO_x ↓by injection pressure↓	n/a	n/a	n/a	[165]
B0 & B100	Cummins ISB 6-cyl. 6.7 L inline turbo-diesel engine. Rated power 325 hp at 2500 rpm CR 17.3 Externally-cooled EGR[f] 1VGT and liquid intercooling Common rail fuel injection	4 operating locations where tailpipe emissions are stringently regulated by the US EPA. 150–185 random combinations of AFR, EGR fraction, rail pressure, and main injection timing 4 each of 4 locations	−50% (at optimal value of AFR, EGR fraction, rail pressure, and start of main injection)	−5% to −42% (at optimal value of lower AFR, higher EGR, rail pressure, and start of main injection)	n/a	n/a	(−) (at optimal value of AFR, EGR fraction, rail pressure, and start of main injection)	[166]
B0, B5, B20, B35, B50, B85	4 cyl. 4 L diesel power generator rated at 55 kW	Variable load: 2.5 kW to 50 kW			(+) CO emissions↓with load↑ and biodiesel content↓	(+) −9% (low loads and B50) −8% (high loads and B85)		[167]
B0 & B100	4-cylinder DI diesel engine Max. power output 46 kW at 2400 rpm	Full load with speed variation form 110 rpm to 2400 rpm and 250 bar of fuel injection pressure. Injection pressure variation: 250 bar, 300 bar and 350 bar.	(−) (for all injection pressure) −16.7%.(from 250 to 350 bar) (Smoke level)	(+) (for all injection pressure) +20% (from 250 to 350 bar)	(−) (for all injection pressure) −28% (from 250 to 350 bar)			[168]
B20 & ULSD	4 cylinder 2.5 L DI diesel engine CR 17.1 Power output 112 kW at 3800 rpm Turbo-Intercooler Common rail fuel injection	13-mode steady-state test cycle (ECE R49) EGR in modes 1–4 Fuel injected twice in idle modes(modes 1, 7, 13) and maximum torque speed modes (modes 2–6) Fuel injected once in rated power speed modes (modes 8–12)	−24% (Particle number, with EGR) −16% (Particle mass, with EGR) −20% (avg smoke emission)	+3.7% (all modes)	−19.6% (all modes)	−35% (all modes)		[147]
B5, B20 & ULSD	Mercedes 4 cyl. 1.7 L DI diesel engine CR 19.5 Rated Power 66 kW at 4200 rpm Common Rail fuel injection	Engine equipped with dSPACE-based flexible engine control system to emulate conventional diesel combustion as well as high efficiency clean combustion (HECC) operation.	Conventional: PM ↓with blend ratio↑(−) (max B20) HECC: PM ↑with blend ratio ↑(slightly)	Conventional: NO_x ↑with blend ratio↑(+) (max B20) HECC: NO_x ↑with blend ratio↑(significantly)	Conventional: 0 (with blend ratio↑) HECC: (−) (B20)	Conventional: 0(with blend ratio↑) HECC: (−) (B20)	0 (Conventional mode) (+) (HECC mode)	[169]

[a] Direct Injection.
[b] Naturally aspirated.
[c] Air cooled.
[d] Compression ratio.
[e] Variable geometry turbocharger.
[f] Exhaust gas recirculation.

Table 5
Review of emissions analysis using rapeseed-biodiesel.

Test fuel/blend	Test equipment specification	Adjustments and/or modification and operating condition	Comparison with diesel fuel performance (% change) in exhaust gas and noise emissions					Ref.
			PM, soot and smoke	NO_x	CO	HC	Noise	
B0 & B100	Lister Petter 1-cyl. pump-line-nozzle DI diesel engine CR 15.5 Maximum power 8.6 kW at 2500 rpm	Constant speed 1500 rpm Variable load: 2 bar, 4 bar and 5 bar EGR variation at each load: 0 and 30%	−52% (avg BSN) (−) (solid PM) BSN (PM)↑with load ↑	+7 to +11%	(−)	−23%(0% EGR) −41%(30% EGR)		[28]
B0 & B100	MAN D2566 MUM 6-cyl. bus engine CR 17.5 Mechanically controlled DI M fuel injection system Max power 162 kW at 2200 rpm	n/a	(−) (Smoke)	(+)	(−)	(+)	(−)	[156]
B0, B5, B20, B40, B50, B80 & B100	Juling SD-1110 1-cyl. CR 16.5 diesel engine Rated power 20 HP (14.7 kW)	n/a	n/a	−0.57 ± 0.2% (B5) −0.9 ± 0.1% (B20) −5.1 ± 0.3% (B40) −3.3 ± 0.1% (B50) +4.1 ± 0.1%(B80) +6.2 ± 0.2%(B100)	CO↓with blend ratio↑ −3.3 ± 0.6%(B5) −8.5 ± 0.8% (B20) −33.8 ± 1.2%(B40) −18.8 ± 1.3%(B50) −32.4 ± 0.4%(B80) −30.5 ± 1.1%(B100)	n/a	n/a	[170]
B0, B1 50% B0+50% RME B3 50% B0+25% RME+25% HOME[a]	4-cyl. 46 kW DI CR 16.1 Maximum power 46 kW at 2400 rpm	Full load and speed 1200 rpm to 2100 rpm	Smoke↓with % RME ↑ −46.29% (B1) −42.11% (B3)	NO_x ↑with %RME↑ +7.2% (B1) +4.98% (B3)	CO↓ with engine speed↑ −15.53% (B1) −9.04% (B3)	n/a	n/a	[171]
B0 & B100	4-cylinder DI diesel engine Max. power output 46 kW at 2400 rpm	Full load with speed variation form 110 rpm to 2400 rpm and 250 bar of fuel injection pressure. Injection pressure variation: 250 bar, 300 bar and 350 bar.	(−) (for all injection pressure) −122% (from 250 to 350 bar) (Smoke level)	(+) (for all injection pressure) +21% (from 250 to 350 bar)	(−) (for all injection pressure) −21% (from 250 to 350 bar)	n/a	n/a	[168]
B0 & B10	Renault Laguna 1.9 L dCi common-rail turbocharged passenger car	1 cold-start New European Driving Cycle – NEDC 1 hot Urban Driving Cycle – UDC (urban sub-cycle of NEDC) 3 real-world driving cycles	−24% (NEDC)	+5% (NEDC) 0 (other driving cycles) NO_x ↑with load (and speed)↑and non-EGR area	0	+15% (NEDC within uncertainty)	n/a	[172]
B0 & B100	Mercedes-Benz 6-cyl. with turbocharger and intercooler Rated power 205 kW CR 17.4	13-mode European Stationary Cycle (ESC)	−55%	+17%	−54%	n/a	n/a	[81]
B0 & B100	MAN D2566 MUM 6-cyl. bus engine CR 17.5 a mechanically controlled DI M fuel injection system Max power 162 kW at 2200 rpm	13-mode European Stationary Cycle (ESC)	−50%(at optimized injection pump timing, −4° CA BTDC than B0)	−25%(at optimized injection pump timing, −4° CA BTDC than B0)	−25%(at optimized injection pump timing, −4° CA BTDC than B0)	−30% (at optimized injection pump timing, −4° CA BTDC than B0)	n/a	[173]
B100	S195 type diesel engine	Optimal adjustments of intake valve close angle, exhaust valve open angle, fuel delivery angle and fuel injection pressure					−2 dB to −4 dB(optimal adjustment)	[174]

[a] HOME: Hazelnut oil methyl ester.

Table 6
Review of emissions analysis using palm-biodiesel.

Test fuel/blend	Test equipment specification	Adjustments and/or modification and operating condition	Comparison with diesel fuel performance (% change) in exhaust gas and noise emissions					Ref.
			PM, soot and smoke	NO_x	CO	HC	Noise	
B0, B100, B75, B50 & B25	KIRLOSKAR TV-1 1-cyl. DI, NA, WC diesel engine Maximum power output: 5.2 kW IT 23.5° bTDC CR 17.5 Injection pressure: 19.6 MPa	Variable load 20% to 100% full load Constant speed 1500 rpm	+9.8% smoke (B25) −19% smoke density(B100) −10% smoke density(B75)	NO_x ↑with load↑(+)	Full load: −21.4% (B25) −35.2% (B50) −35.2% (B75) −52.9% (B100)	+9.52% (B25) −9.53% (B50) −19.05% (B75) −38.09% (B100)		[157]
B0, B20 & B100	4-cyl. DI 4.5 L diesel engine Rated Power 115 kW at 2400 rpm CR 16.57 high pressure common-rail fuel injection VGT with EGR	Variable load: 67.8, 203.4, and 406.7 N-m variable engine speeds: 1400, 1900, and 2400 rev/min	Smoke conc. (−) (B100) 0 (B20)	(−) (B20, 1400 rpm, mid load, with EGR)				[175]
B0, B20 & B50	3-cyl. 2.5 L Perkins AD 3–152 Maximum engine power of 44 kW at 2132 rpm	8-mode cycle		+0.32 to +25% (B50) −1.4 to +24% (B20)	−27% (avg,B50) −20% (avg,B20)		−75% (max, B50) Sound attenuation↑with blend ratio↓	[46]
B0, B10, B20, B30, E16P10 (16 vol% bio-solution+10 vol% B100+74 vol% B0, an additional 1 vol% of surfactant), E16P20, E16P30	4-cyl. DI WC diesel-engine generator (non-catalyst) Maximum power of 40 kW at 2600 rpm Maximum injection pressure is 19.5 MPa	Constant load: 125 Nm, 75% of total torque load	PM in mg/L & mg/kWh −45.6% & −45.5% (B10) −21.2% & −20.6% (B20) −9.58% & −7.02% (B30) −89.2% & −88.6%, (E16P10) −90.1% &−89.4% (E16P20) −89.8% & −88.8% (E16P30)					[176]
B0 & B10	2.2 L PSA 4-cyl. turbocharged intercooled diesel engine CR 18 Max power 96 kW at 4000 rpm Common rail Injection system	Low speed,low load(1500 rpm, 30 Nm) Low speed, high load (1500 rpm, 170 Nm) High speed low load (350 rpm, 75Nm) High speed, high load (3500 rpm, 170 Nm)	Smoke −14% (low load, low rpm) +118% (high load, low speed)+13% (low load, high speed) +60% (high load, high speed)	+1% (low load, low rpm) −1% (high load, low speed)−6% (low load, high speed) +2% (high load, high speed)				[172]
B0, B5, B20 & ULSD	Cummins In-line 4-cyl. turbo- intercooler Maximum power 88 kW at 2800 rpm CR 17.5	Constant speed: 1500 rpm and 2500 rpm Variable load: 0 Nm, 75 Nm, 150 Nm, 225 Nm and 300 Nm	−28.8% (B20) Smoke opacity↑with load↑ Smoke opacity↓with blend ratio↑	NO_x ↑with with blend ratio↑(+)				[177]
B0,B20 & B20X(B20 with X% NPAA[a])	Isuzu 4-cyl. WC, IDI CR 21 Rated power 39 kW at 5000 rpm	Constant load 50 Nm Constant speed 2250 rpm		+3.5% (B20) −20% (B20X)	−42% (B20) −71% (B20X)	−29% (B20X) −17% (B20)		[178]

[a] NPAA: 4-Nonyl Phenoxy acetic acid.

Table 7
Review of emissions analysis using jatropha-biodiesel.

Test fuel/blend	Test equipment specification	Adjustments and/or modification and operating condition	Comparison with diesel fuel performance (% change) in exhaust gas and noise emissions					Ref.
			PM, soot and Smoke	NO_x	CO	HC	Noise	
B0, B5, B10, B20, B50 & B100	3.3-L 4-cyl. DI turbocharged intercooled diesel engine High-pressure common-rail fuel system Rated power output 79 kW at 3200 rpm	Variable load: 10%, 25%, 50% & 75% full loadConstant speed: 2000 rpm	Smoke↑with load↑bFor B100 −85.7% (10% full load) −79.3% (25% full load) −80.0% (50% full load) −76.9% (75% full load)	high load +1.02%(B5) +2.06%(B10) +4.74%(B20) +5.71%(B50) +13.9%(B100)0(low and medium load, B5,B10,B20 & B50)	CO ↓with load↑(+) (low load) (−) (high load)	HC↓ with blend ratio↑ −46% (max B100,high load)		[180]
B0, B5, B10, B20, B30 & B100	Kirloskar 1-cyl. AC, DI, NA diesel engine	Variable load: 0%, 20%, 40%, 60%, 80% & 100% load	(−) (Smoke density) Smoke density↑ with load ↑	NO_x ↑with load ↑	CO↓ with blend ratio ↑	(−) HC↑ with load↑		[181]
B100	Kirloskar 1-Cyl. DI, bowl-in-piston diesel engine CR 17.5 speed (constant) 1500 rev/min Rated power 4.4 kW Injection pressure 200 bar Injection timing 23° BTDC	Antioxidant additives L-ascorbic acid, α tocopherol acetate, butylated hydroxytoluene (BHT), *p*-phenylene diamine (PPDA) and ethylene diamine (EDA) Different mixtures (0.005, 0.015, 0.025, 0.035, 0.05%-m) Constant speed: 1500 rpm		−43.55% (PPDA and 0.025%-m)	(+)	(+)		[36]
B0, B10, B20, B30, B40 & B50	Kirloskar 1-Cyl. DI, AC diesel engine CR 17.5 speed 1500 rev/min rated power 4.4 kW Injection pressure 200 bar	Variable load	(+) Smoke opacity↑ with load↑ and % JME↑	(+)NO_x ↑with load↑	(−) CO↓ with blend ratio↑	(−)		[179]
B0 & B100	Greaves cotton engine type DI, NA, AC 1-cyl. diesel engine CR 18 Maximum power 5.59 kW at 3600 rpm IT 345CAD	Variable load: 5Nm to 15 Nm variable speed: 1800 rpm and 3200 rpm Variable IT: 345 ± 5 CAD	−1.5% (340 CAD, 15 Nm)	+20% (340 CAD, 15 Nm) (−) (350 CAD)	−1.2% (340 CAD, 15 Nm)	Min HC(340 CAD) −1.5% (340 CAD, 15 Nm)		[182]
HSD & B20	SWARAJ MAZDA 4-cyl. DI WC engine IT 10° bTDC CR 17:1 Rated Power 58.2 kW@ 3000 rpm	Variable load: Idling, 50%, 75% and 100% load Constant speed: 1800 rpm	PM mass concentrations↑with Load↑					[183]
B0,B5 & B10	Yanmar 1-cyl. NA Engine CR 17.7 Max. power 7.7 kW IT 17° bDTC	Constant speed: 2300 rpm Throttle position: 100% and 80%		100% throttle +4%(B5) +6.25% (B10) 80% throttle +9.5% (B5) +17.0% (B10)	100% throttle −17.26% (B5) −25.92% (B10) 80% throttle −20.70% (B5) −33.24% (B10)	100% throttle −8.96% (B5) −11.25% (B10) 80% throttle −16.28% (B5) −30.23% (B10)	(−)	[112]
B0 & B100		Variable load: no load, 1/4 th load, 1/2 load, 3/4 th load and full load					−1.5dB (SPL, max)	[184]

- Noise attenuation increases with ester percentage in blend
- Noise reduction by Palm biodiesel is also significant

Emission reduction technique as suggested from review table:

- EGR again can be used for effective NO_x reduction
- Use of additives or bio-solution has a positive impact on emission reduction

5.4. *Jatropha biodiesel*

Jatropha biodiesel is a second generation biodiesel produced from the seeds of the *Jatropha curcas*. Jatropha oil has medium percentage of saturation (about 21.1%) and unsaturation (about 78.9%) as compared to other reviewed oil. Thus cetane number (range: 53–59), iodine value (range: 93–109 mg I/g) and density (range: 862–886 kg/m^3) also fall between the two extremes (Table 2). It has a higher percentage of longer chain unsaturation, similar to soybean oil; resulting in similar densities. Elango and Senthilkumar [179] evaluated combustion characteristics of a single cylinder diesel engine fuelled with different jatropha biodiesel blends. They found higher ignition delay for jatropha biodiesel blends. Table 7 emission data shows a considerable spread as there are variations in feedstock source, test equipment and operating condition, data acquisition instrument accuracy and ambient conditions. The following decisions can be made:

- Smoke emissions are drastically reduced by using biodiesel but with load and methyl ester percentage in blend, smoke emission increases
- PM mass concentration and NO_x emission increase with load
- Both CO and HC emission increases with load and decreases with FAME content and generally reduced by using it
- Antioxidant additives have a negative effect on CO and HC emission
- Noise emission is reduced by it
Emission reduction technique as suggested from review table:

- Injection timing retardation and antioxidant additives addition can be pathway to NO_x reduction
- Injection timing advance will have positive effect on PM, smoke, HC and CO reduction

5.5. *Cottonseed biodiesel*

Cottonseed biodiesel is a second generation biodiesel produced from cottonseed oil, which is produced from press cottonseed. Cottonseed oil has lower percentage of unsaturation (about 71.8%) and higher percentage of saturation (about 28.2%) as compared to jatropha as in Table 1. These have effect on physical and thermal properties of Cottonseed oil methyl ester (COME). Cottonseed oil has highest linoleic acid percentage (about 55.2%) i.e., poly-unsaturation compared to others which affects physical and thermal properties of COME. Iodine value (range: 90–119 mg I/g) of COME is relatively higher because of higher poly-unsaturation. Cetane number (range: 55–60) and density (range: 872–885 kg/m^3) are also compared to JOME depending on the feedstock acquisition place. Table 8 emission data shows a considerable spread as there are variations in feedstock source, test equipment and operating condition, data acquisition instrument accuracy and ambient conditions. The following decisions can be made:

- Considerable PM and smoke reduction is attained by COME
- NO_x emission showed a considerable spread from −22 to +39% by COME combustion

Table 8
Review of emissions analysis using cottonseed-biodiesel.

Test fuel/blend	Test equipment specification	Adjustments and/or modification and operating condition	Comparison with diesel fuel performance (% change) in exhaust gas and noise emissions					Ref.
			PM, soot and smoke	NO_x	CO	HC	Noise	
B0 and B30(70% B0+ 30% B100) B100(50% SME+50% CME)	Mercedes Benz 6-cyl. in-line, DI, WC, turbo-after cooled engine Maximum power 177 kW@2600 rpm CR 18 IT 5 ± 1° bTDC	At idling speed 950 rpm Coolant temp. 80 °C.	(+) (Peak soot level) (+) (Smoky period)	n/a	n/a	n/a	0	[185]
B0,B20, BK20 (80% B100+20% kerosene)	Rainbow–186 1-cyl.AC DI engine CR 18 Maximum power 7.46 kW	Variable speed: 1250 to 2500 rpm	(−) Smoke (BK20)	−6 to −10% (BK20 to B20) 0(B20)	CO↓with speed↑(−) (B20, BK20)	n/a	n/a	[186]
B0, B5, B20, B50, B75 & B100	Rainbow–186 1-cyl.AC DI engine CR 18 Maximum power 7.46 kW	Variable speed: 1250 to 2500 rpm	n/a	(+) B5 (−) (B20, B50, B75 & B100)	(−) Min (B50, B75 & B100)	n/a	n/a	[187]
B20	Lambardini 3.95 L 1-cyl. DI, AC engine CR 18	ECE (Euro 2) drive cycle	n/a	−10 to −22%	−16 to −33%	n/a	n/a	[41]
B0,B10,B20,B30	1-cyl. WC NA, DI diesel engine CR 16.5 Rated power 4.476 kW at 1800 rpm	Constant speed: 850 rpm variable load	−24% max (B20, PM) −14% max (B10, smoke)	+10% (B30)	−24% (B30)	n/a	n/a	[188]
B0, B100	Cummins 6-cyl. 5.9 L DI with turbocharger & intercooler CR 17.5 Rated power 136 kW at 2500 rpm High pressure common rail	Constant speed: 1500 rpm Variable load: 0.256 MPa, 0.512 MPa, 0.768 MPa, 1.024 MPa & 1.280 MPa	−63%	+9.5%	−13%	−50%	n/a	[158]
B100	Antor 1-cyl. NA engine test bed & fuel heating equipment. CR 18 Maximum speed 3600 rpm	B100 preheated up to 30°, 60°, 90° and 120 °C Variable speed: 1800 to 3200 rpm	n/a	+11.21 to +39.1%	−14.40 to −45.66%	n/a	n/a	[189]
B100	Lombardini 3.95 L 1-cyl. DI, AC engine CR 18 Maximum power 6.25 kW Maximum engine torque 19.6 Nm at 2200 rpm	Constant load Variable speed 3400, 3100, 2800, 2500, 2200, 1900, 1600, and 1300 rpm	n/a	−10 to −22%	−35–71%.	n/a	n/a	[190]

- Dramatic reduction of CO and HC is observed by most of the researchers
- Noise emission did not show any considerable change when COME is used

  Reduction techniques of emissions as suggested from review chart:
- Kerosene addition results in lower NO_x, Smoke and CO emission.

6. Conclusion

In the industrial economy of any country, diesel fuel plays an important role. These fuels run a major part of the transport sector and their demand is increasing steadily. Therefore, increasing combustion of petroleum based fuels in internal combustion engines impact on air quality, human health and global warming. Replacement of a portion of diesel fuel with biofuel will mitigate the above mentioned issues. Renewable energy such as biofuel is found to be the fastest growing energy form. Transport and basic industry sectors are the main prospective sectors for utilizing it. Many countries are producing and exporting biofuels but not utilizing to great extent as they are less conscious on health hazard and environmental pollutants. Based on the extensive use in USA, European region and some tropical regions like India, Malaysia, Indonesia etc, total five specific biodiesels obtained from edible and non-edible oils such as soybean, rapeseed, palm, jatropha and cottonseed were critically reviewed. Biodiesel produced from newer sources is becoming more significant in providing world energy requirements for transportation compared to conventional sources as use of conventional sources are now being highly criticized.

From the review of five selected biodiesels the following findings are summarized:

- Biodiesel molecular structure and chemical composition have a substantial impact on combustion, noise and emissions because of its considerable oxygen content.
- The compositional profiles of selected vegetable oils are dominated by five fatty acid species: palmitic, stearic, oleic, linoleic, and linolenic acid. It was found that rapeseed oil has the highest percentage of unsaturation (about 94.6%) followed by soybean (about 84.7%), Jatropha (about 78.9%), cottonseed oil (about 71.8%) and Palm oil (55.35%).
- In general biodiesel and its blends have strong beneficial effect on HC, CO, and PM emissions but adverse effect on NO_x emissions.
- Rapeseed, jatropha and cottonseed excel in reduction of PM, smoke level and HC emission, soybean and palm are superior in PM and CO emission reduction.
- Uses of kerosene, anti-oxidants or bio-solution provide effective solution to increasing NO_x issue.
- Noise emission also showed a decreasing trend and good noise quality was observed with biodiesel fuel. Palm showed the highest overall engine noise attenuation.
- Optimal adjustment of engine operating parameters together with biodiesel use will provide an adequate advantage to the environment and human health.

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